Linear and Non-Linear Features of Surface EMG during Fatigue and Recovery Period

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Abstract. Aim: To investigate possible factors that affect the sEMG signal features, we analyzed the sEMG signals in bicep bracii(BB) muscle during fatiguing isometric flexions and recovery periods across a range of force levels. Method: Twelve males performed isometric elbow flexions at 40%, 60%, 80% and 100% of their maximal voluntary contraction (MVC) with joint angle keeping at 90°. And then they performed 3 seconds of MVC at the 2nd, 4th, 6th, 8th, 10th, 20th, 30th, 60th and 120th second respectively during recovery periods. SEMG signals in BB were analyzed using both linear and non-linear methods to get parameters such as average EMG (AEMG), mean power frequency (MPF), Lempel-Ziv complexity (C(n)) and Determinism% (%DET). Results. Non-linear parameter C(n) decreased whereas %DET increased during fatiguing flexions. There was no regularity in AEMG in recovery periods. MPF, C(n) and %DET recovered significantly only by seconds rest, and they regressed rapidly in the initial 10 seconds and then slowed down in the later. Conclusions. The rapid changes of SEMG linear and non-linear parameters in recovery periods suggested that central controlling factor may play a more important role in shaping sEMG signals.

Keywords: fatigue, surface electromyography, complexity, recurrence quantification analysis

1 Introduction

Local muscle function and activation level could be reflected by sEMG signals under well-controlled conditions. The related studies were paid more and more attentions by researchers in rehabilitation medicine, ergonomics and sports science[1]. The previous studies demonstrated that the sEMG linear time domain parameters such as integrated EMG (iEMG), AEMG increased with muscle fatigue development while the frequency domain parameters such as median frequency (MF), MPF decreased[2,3]. Nevertheless, the neuromuscular system is very complex and sEMG signal itself bears non-stationary and non-linear features. Therefore more and more attentions were paid to the non-linear analysis methods developed in recent years. Webber C.L. et al. developed recurrence quantification analysis (RQA) and found that the increases in %DET of sEMG signal could reflect the extend of local muscle fatigue[4]. YE Wei et al. reported that C(n) decreased during muscle fatiguing progresses[5,6]. Their studies suggested that sEMG signal became more regular and more orderly when the muscle became more fatigue. We analyzed the changes of sEMG parameters during fatiguing elbow flexions across a range of force levels, and also analyzed the sEMG signals taking from the immediate recovery periods in order to investigate the possible mechanism affecting the sEMG features.

2 Methods

2.1 Experimental protocol

Twelve healthy males (25±4.6y, 175.1±5.8cm, 73.8±6.0kg) performed 40%, 60% and 80%MVC fatiguing isometric elbow flexions until task failure with their right arm. And they performed 100%MVC elbow flexion until the force feedback reduced to 50%MVC for 3 continuous seconds. Every subject was asked to exert a maximal voluntary contraction for about 3 seconds at 2nd, 4th, 6th, 8th, 10th, 20th, 30th, 60th and 120th second respectively during recovery periods. One fatiguing effort only provided one MVC measure in recovery periods to ensure that every fatiguing flexion was based on non-fatigue elbow joint muscles. The order of MVC measures (at 9 rest intervals) after fatiguing flexion were randomized and at least 1.5 hours rest was given between testing sessions.

2.2 SEMG recording and analysis

The raw sEMG signal were gathered using ME3000P...
system (Mega Inc., Finland) with disposable electrodes (1 cm radius, 2cm inter-electrode distance, self-adhesive) at BB muscle belly. The signal were sampled at 1000Hz and stored on computer for later analysis.

We calculated two typical linear sEMG parameters (AEMG and MPF) with MegaWin2.2 software and two non-linear parameters (C(n) and %DET) with self-made program based on the definition of Lempel-Ziv complexity and RQA software provided by Webber C.L. All parameters were calculated with 1024 data point window. Based on previously related studies, the calculating settings of %DET were as follows: \( r=4, \ m=10, \ n=1024, \ \text{shift data } =1024, \ \text{radius}=15\%\text{max distance }, \ l=2. \)

2.3 Statistical analysis

The differences of sEMG parameters between the exhaustions in fatiguing flexions and the 2nd second in recovery periods were assessed by the two-tailed t-test. The effects of recovery time and force level on sEMG parameters during recovery period were assessed by two-way ANOVA. The statistical analysis software was SPSS11.0.

3 Results

Changes in AEMG and MPF during fatiguing flexions were showed in Fig.1 and Fig.2. Non-linear parameter C(n) declined linearly while %DET increased in fatiguing progress (Fig.3, Fig.4). The changes in four sEMG parameters (signals were recorded in MVC measurements) in recovery period were showed in Fig.5~8. MPF, C(n) and %DET showed marked recovering trend immediately after
fatiguing elbow flexions except AEMG. The recovery of MPF, C(n) and %DET could be divided into rapid phase (about initial 10 seconds) and later slow phase.

When the fatiguing flexion near task failure (exhaustion) we assumed that the subject was performing maximal efforts regardless of force levels. There were significant differences in all sEMG parameters between those at the exhaustion and those at 2nd second in recovery periods (P<0.001). Two-way ANOVA indicated that recovery time exerted remarkable effect on MPF, C(n) and %DET (P<0.001) except AEMG (p=0.848). No force level effect in recovery periods was found (p>0.05) on sEMG features and there was no significant interaction between force level and recovery time (p>0.05).

4 Discussion

The changes of linear parameter AEMG and MPF during fatiguing isometric contractions in our studies were similar to the results reported by many pioneer researchers[2,3,7,8]. Lempel-Ziv complexity (C(n)) was often used to depict chaos signals and was widely applied in analyzing electroencephalograph (EEG). C(n) declined linearly along fatiguing progress in this study suggesting that sEMG signals became less complex in fatigued muscles. RQA method offered an efficient tool to detect the regularity within data (signals) and was more effective for processing non-stationary signals. Researchers used Determinism% (%DET) to represent the periodicity of a given biological signal[9]. Considering the decreases in C(n) and the increases in %DET in this study, we thought that the recruitment of motor unit synchronized gradually with the development of local muscle fatigue (LDF).
Almost all researchers thought that the changes in sEMG features were effected by both central and peripheral factors. And many held that the decreases in MPF or MF during muscle fatiguing progress were the result from the decrease in muscle fiber conduction velocity (MFCV) caused by [H+] accumulation in muscle cells. Nevertheless, there were more and more evidences against this point of view. Masuda et al. found that MPF declined during both static and dynamic contractions while MFCV declined only during static contractions and showed no marked changes during dynamic contractions\(^{[10]}\). MPF also declined in Mcardle’s patients (unable to produce lactates for the lack of phosphorylase) during fatiguing exercises\(^{[11]}\). WANG et al. found that MPF in a non-fatigue antagonist muscle declined similar to that in agonist muscle and attributed this phenomenon to the “co-activation hypothesis”\(^{[12]}\).

The present study investigated sEMG features in recovery periods after fatiguing isometric contractions across a range of force levels. The results showed that AEMG, MPF, C(n) and %DET recovered remarkably only after two seconds of rest compared with those at exhaustion. Moreover, the regular changes in sEMG non-linear parameter C(n) and %DET during fatiguing progress and recovery period suggesting that the central drive may play an important role in shaping the sEMG signals.

**5 Conclusions**

5.1 Non-linear sEMG parameter C(n) and %DET exhibited regular changes during fatiguing isometric contractions above moderate force levels.

5.2 SEMG signal became less random and showed more periodicity with the progress of local muscle fatigue.

5.3 The rapid recovery of sEMG features suggested that the central controlling strategies may play an important role in shaping sEMG signals.

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**References:**


